

****TITLE****

*ASP Conference Series, Vol. **VOLUME**, **PUBLICATION YEAR***

****EDITORS****

The Origin of Hot Subluminous Horizontal-Branch Stars in ω Centauri and NGC 2808

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Abstract. Hot subluminous stars lying up to 0.7 mag below the extreme horizontal branch (EHB) are found in the ultraviolet (UV) color-magnitude diagrams of both ω Cen (D'Cruz et al. 2000) and NGC 2808 (Brown et al. 2001). In order to explore the evolutionary status of these subluminous stars, we have evolved a set of low-mass stars continuously from the main sequence through the helium-core flash to the HB for a wide range in the mass loss along the red-giant branch (RGB). Stars with the largest mass loss evolve off the RGB to high effective temperatures before igniting helium in their cores. Our results indicate that the subluminous EHB stars, as well as the gap within the EHB of NGC 2808, can be explained if these stars undergo a late helium-core flash while descending the white-dwarf cooling curve. Under these conditions the convection zone produced by the helium flash will penetrate into the stellar envelope, thereby mixing most, if not all, of the envelope hydrogen into the hot helium-burning interior, where it is rapidly consumed (Sweigart 1997). This phenomenon is analogous to the “born-again” scenario for producing hydrogen-deficient stars following a very late helium-shell flash. This “flash mixing” of the stellar envelope greatly enhances the envelope helium and carbon abundances and, as a result, leads to a discontinuous jump in the HB effective temperature. We argue that the EHB gap in NGC 2808 is associated with this theoretically predicted dichotomy in the HB morphology. Using new helium- and carbon-rich stellar atmospheres, we show that these changes in the envelope abundances of the flash-mixed stars will suppress the UV flux by the amount needed to explain the hot subluminous EHB stars in ω Cen and NGC 2808. Moreover, we demonstrate that models without flash mixing lie, at most, only ~ 0.1 mag below the EHB, and hence fail to explain the observations. Flash mixing may also provide a new evolutionary channel for producing the high gravity, helium-rich sdO and sdB stars.

1. Introduction

Extreme horizontal-branch (EHB) stars occupy the hot end of the horizontal branch (HB) in globular clusters with extended blue HB tails. The envelope masses of these stars are too small ($< \sim 0.02 M_{\odot}$) to sustain hydrogen-shell burning, and thus nearly all of their luminosity comes from helium burning in the core. Recent observations have discovered an unexpected population of hot stars lying below the canonical EHB in the UV color-magnitude diagram (CMD) of ω Cen (D’Cruz et al. 2000 and references therein). In the present paper we will use new UV observations of the globular cluster NGC 2808 to explore the origin of these subluminescent EHB stars and will suggest that these stars may be the progeny of stars which underwent extensive mixing during a delayed helium flash on the white-dwarf (WD) cooling curve (Brown et al. 2001).

Our data for NGC 2808 were obtained in the far-UV (FUV, $\lambda \sim 1600 \text{ \AA}$) and near-UV (NUV, $\lambda \sim 2700 \text{ \AA}$) bandpasses of the Space Telescope Imaging Spectrograph (STIS). The HB of NGC 2808 is bimodal with a large gap between the blue HB (BHB) and red HB (RHB) stars. In addition, NGC 2808 has a very long blue HB tail that is punctuated by two gaps: one between the EHB and BHB and one within the EHB itself (Sosin et al. 1997; Walker 1999; Bedin et al. 2000). Our STIS CMD (Figure 1) shows the following features:

- The gap between the EHB and BHB at $m_{FUV} - m_{NUV} \sim -1$ mag is well detected, as is the gap between the BHB and RHB at $m_{FUV} - m_{NUV} > 0$ mag. The gap within the EHB seen in optical CMDs is not present.
- There is a large population of hot subluminescent HB stars, previously known to exist only in ω Cen (D’Cruz et al. 2000). Out of a total of 75 EHB stars, 46 are fainter than the canonical zero-age horizontal branch (ZAHB).
- 5 luminous post-EHB stars are found at $m_{FUV} < 15.5$ mag.

2. Canonical Evolution through the Helium Flash

To study the origin of the hot subluminescent EHB stars, we computed a set of evolutionary sequences which followed the evolution of a low-mass star continuously from the main sequence through the helium flash to the ZAHB. All sequences had the same heavy-element abundance Z of 0.0015, corresponding to $[\text{Fe}/\text{H}] = -1.31$ for $[\alpha/\text{Fe}] = 0.3$, and an initial main-sequence mass M of $0.862 M_{\odot}$, corresponding to an age of 13 Gyr at the tip of the RGB. The sequences only differed in the extent of mass loss along the RGB which we specified by varying the mass-loss parameter η_R in the Reimers formulation from 0 to 1. Our purpose was to determine if mixing between the helium core and hydrogen envelope might occur during the helium flash, as found previously by Sweigart (1997).

A representative sample of our evolutionary tracks is shown in Figure 2. For $0.0 \leq \eta_R < 0.740$ the helium flash occurs at the tip of the RGB. As the mass loss increases, however, the models peel off the RGB and evolve to high effective temperatures before igniting helium (so-called “hot He-flashers”; Castellani & Castellani 1993; D’Cruz et al. 1996). For $0.740 \leq \eta_R \leq 0.817$ the helium flash occurs between the tip of the RGB and the top of the WD cooling curve.

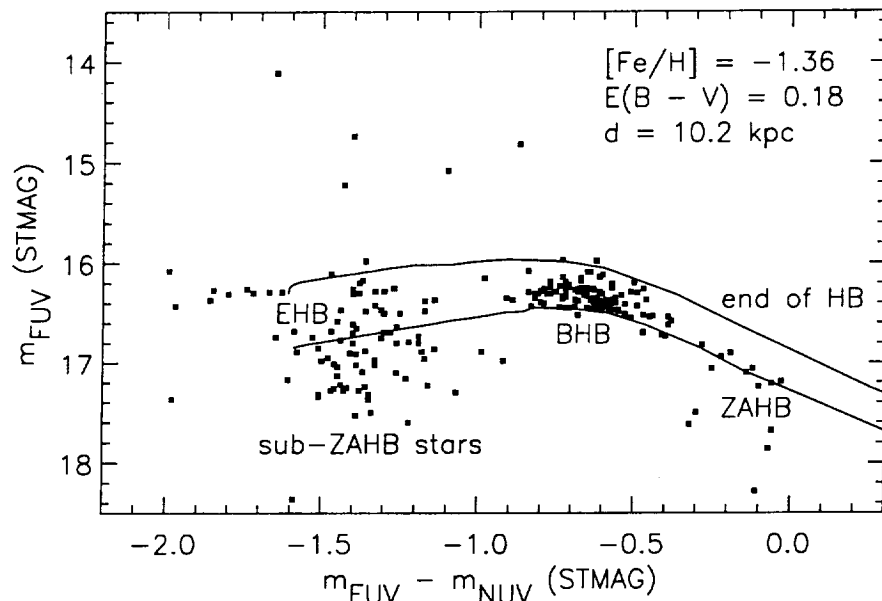


Figure 1. STIS UV color-magnitude diagram for NGC 2808. The theoretical loci for the ZAHB and the end of the HB phase (solid lines) were transformed to the observational plane using the indicated cluster parameters. Note the large population of hot sub-ZAHB stars.

In all sequences with $\eta_R \leq 0.817$ the flash convection zone produced by the high helium-burning luminosity (peak $L_{He} \sim 10^{10} L_{\odot}$) failed to reach the hydrogen envelope by ~ 1 pressure-scale height. Thus mixing between the helium core and the hydrogen envelope does not occur if a star ignites helium either on the RGB or during the evolution to the top of the WD cooling curve. In these cases we confirm the canonical assumption that the helium flash does not affect either the envelope mass or composition.

3. Flash Mixing on the White-Dwarf Cooling Curve

The canonical evolution described above changes dramatically when the helium flash occurs further down the WD cooling curve (Figure 2). As a star descends the cooling curve, the entropy barrier of its hydrogen shell decreases (Iben 1976). As a result, the flash convection is then able to penetrate deeply into the hydrogen envelope (Sweigart 1997; Brown et al. 2001). The protons captured by the flash convection will be mixed into the helium-burning core while helium and carbon from the core will be mixed outward into the envelope. The calculations of Sweigart (1997) indicate that this “flash mixing” will consume most, if not all, of the envelope hydrogen while simultaneously enriching the envelope in helium and carbon. All of our sequences with $0.818 \leq \eta_R \leq 0.936$ encountered flash mixing. These sequences were stopped at the onset of mixing due to the numerical difficulty of following the proton mixing and nucleosynthesis. Sequences with $\eta_R \geq 0.937$ did not ignite helium and thus died as helium white dwarfs.

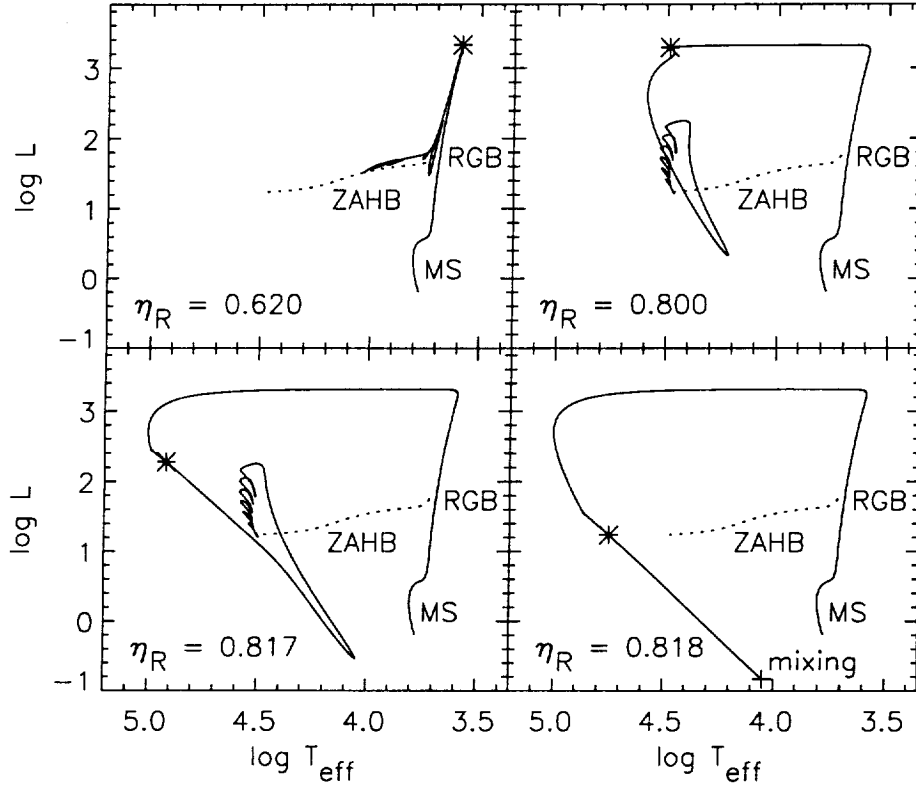


Figure 2. Evolutionary tracks from the main sequence (MS) through the helium flash to the ZAHB for 4 values of the mass-loss parameter η_R . The peak of the helium flash (*) is indicated. The flash convection reached the hydrogen envelope at the end of the $\eta_R = 0.818$ track (+).

Flash mixing is a consequence of the basic properties of the stellar models and hence should occur whenever a star ignites helium on the WD cooling curve. Analogous mixing occurs during a very late helium-shell flash according to the “born-again” scenario for producing hydrogen-deficient stars (Iben 1995 and references therein).

EHB evolutionary tracks for both canonical ($\eta_R \leq 0.817$) and flash-mixed ($0.818 \leq \eta_R \leq 0.936$) sequences are plotted in Figure 3. The canonical (i.e., unmixed) models have the same H-rich envelope composition as the pre-helium flash models. The ZAHB models for the flash-mixed tracks were obtained by changing the envelope composition to mimic the effects of flash mixing. We considered both He + C-rich and He-rich envelope compositions for these flash-mixed models (see caption of Figure 3). For comparison the bottom panel of Figure 3 shows a set of tracks with $0.818 \leq \eta_R \leq 0.936$ which have the same H-rich envelope composition as the canonical models.

Several features of Figure 3 deserve comment. First, there is a well-defined high temperature limit to the canonical EHB at an effective temperature T_{eff} of

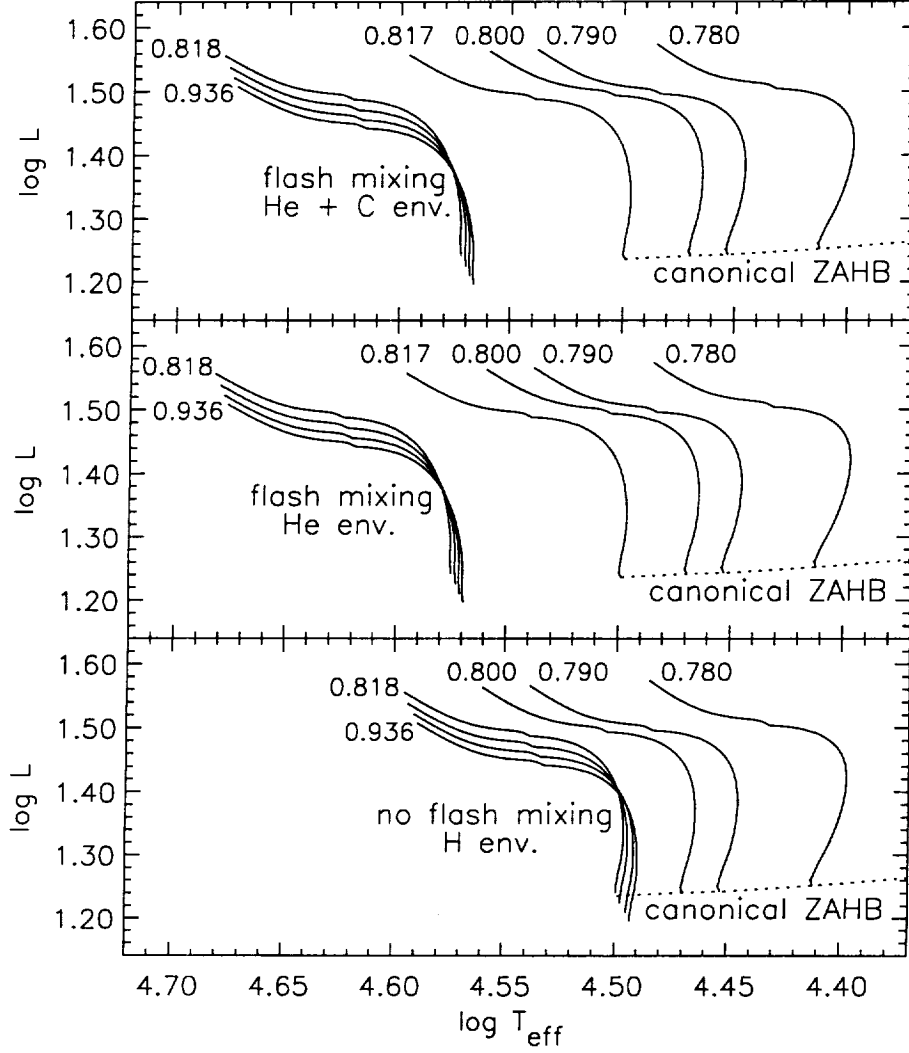


Figure 3. EHB evolutionary tracks for canonical sequences ($\eta_R \leq 0.817$) and sequences with flash mixing ($\eta_R = 0.818, 0.860, 0.900, 0.936$). The ends of the tracks are labeled by the value of η_R . The flash-mixed tracks in the top panel have an envelope helium abundance Y of 0.96 and a carbon abundance C of 0.04 by mass, with the other heavy elements at their cluster abundances. The flash-mixed tracks in the middle panel are the same except that $Y = 1.0$ and $C = 0.0$. The corresponding tracks in the bottom panel have the same H-rich envelope composition as the canonical tracks. Note the temperature gap between the He + C and He flash-mixed tracks and the canonical tracks. In contrast, the H tracks, which ignore flash mixing, lie at the hot end of the canonical EHB.

$\sim 31,500$ K for the present metallicity. Within the canonical framework it is not possible to produce hotter EHB stars regardless of the extent of mass loss along the RGB. Second, the flash-mixed tracks are separated by a gap of ~ 6000 K in T_{eff} from the hot end of the canonical EHB. As a consequence, flash mixing leads to a sharp dichotomy in the properties of the EHB stars. The change from canonical to flash-mixed evolution occurs over an interval of only 0.001 in η_R , corresponding to a mass-loss difference of only $10^{-4} M_{\odot}$.

4. Nature of the Subluminous EHB Stars

In order to compare our EHB models with the STIS data, we computed new stellar atmospheres for both H-rich and H-depleted compositions. The spectral energy distribution for a canonical EHB star is compared to the spectra for 2 flash-mixed stars with He + C-rich and He-rich atmospheres in Figure 4. The enhanced helium abundance in the flash-mixed stars reduces the hydrogen opacity below 912 \AA so that more of the flux is radiated in the extreme UV at the expense of the flux at longer wavelengths. Enhancing the carbon abundance along with helium restores some of this extreme UV opacity, but the resulting spectrum is still redder and fainter in the far-UV than a normal spectrum.

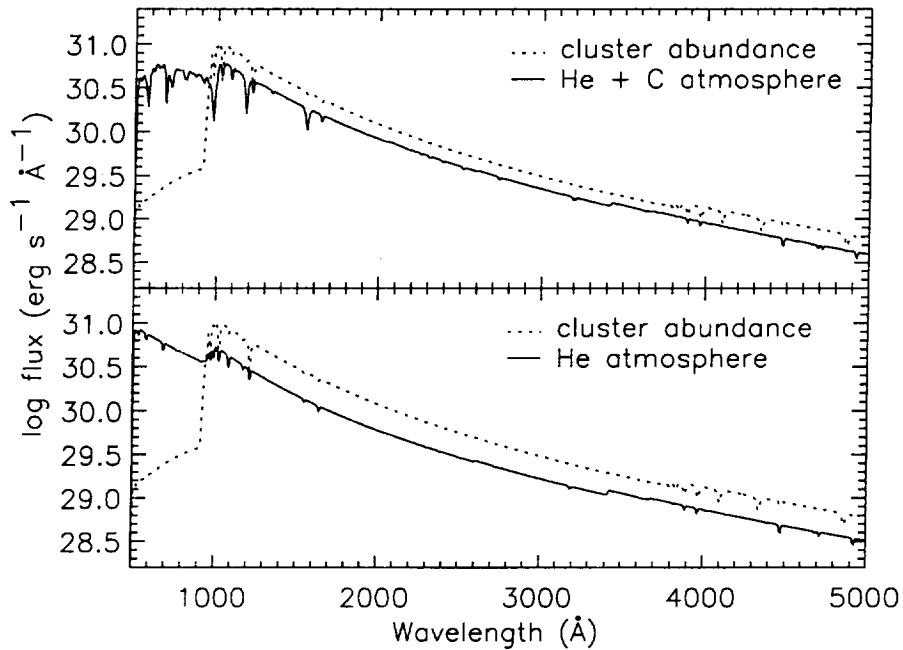


Figure 4. Spectral energy distribution for a canonical EHB star ($T_{\text{eff}} = 31,000$ K, dashed lines) with the nominal cluster abundance of NGC 2808 and for two flash-mixed stars ($T_{\text{eff}} = 37,000$ K, solid lines) with either a He + C (upper panel) or He (lower panel) envelope composition. Note that the flash-mixed stars are fainter in the UV.

Using these He + C-rich and He-rich stellar atmospheres, we translated the ZAHB models from the flash-mixed sequences to the STIS CMD (see Figure 5). The flash-mixed models show the same dramatic drop in the far-UV luminosity as the STIS data. This drop can be attributed to 1) the lower far-UV flux in the spectral energy distribution of the flash-mixed models (see Figure 4) and 2) the larger bolometric correction due to their higher temperatures (see Figure 3). Evolution off the ZAHB will fill in the region between these flash-mixed models in Figure 5 and the canonical ZAHB. Radiative levitation of Fe would shift the flash-mixed models redward, possibly explaining the color spread of the subluminous stars. In contrast, the $\eta_R = 0.860$ ZAHB model with a normal H-rich envelope in Figure 5 lies just ~ 0.1 mag fainter than the hot end of the canonical EHB, a consequence of its slightly smaller core mass ($\Delta M_c \sim 0.004 M_\odot$). It is clear therefore that hot He flashers which ignore flash mixing cannot explain the subluminous stars in either ω Cen or NGC 2808.

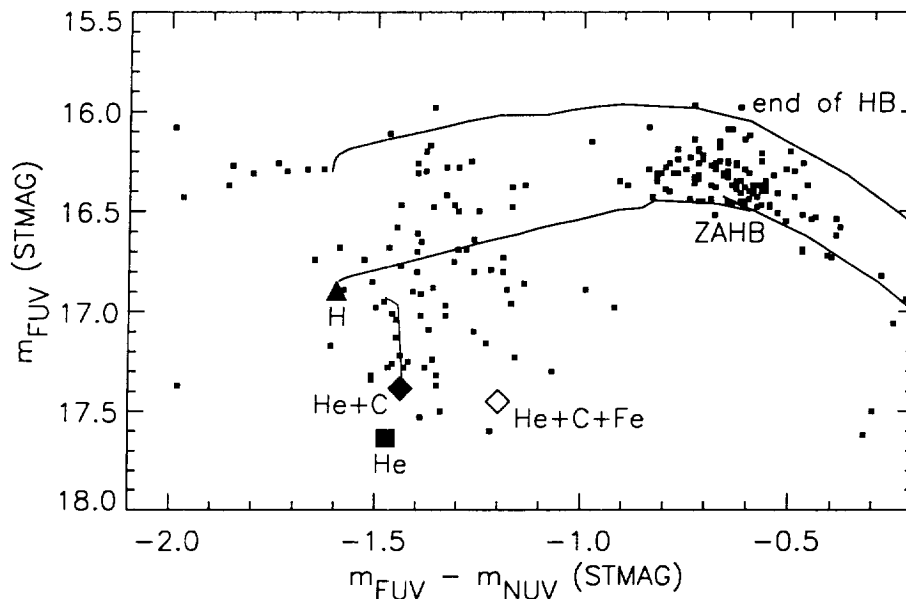


Figure 5. Location of the $\eta_R = 0.860$ ZAHB models in the STIS CMD of NGC 2808. The ZAHB model with a normal H-rich envelope (filled \triangle) lies near the hot end of the canonical EHB and thus cannot explain the subluminous stars. However, the flash-mixed ZAHB models with He + C (filled \diamond) or He (filled \square) envelopes lie well below the canonical EHB. Such models evolve to brighter luminosities (thin line), filling the area under the canonical EHB. Radiative levitation of iron to $[\text{Fe}/\text{H}] = +1$ would move the He + C model redward (open \diamond).

Optical CMDs also show a gap within the EHB of NGC 2808. We have plotted our ZAHB models in the $(B - V, V)$ CMD to see if the temperature difference between the flash-mixed and canonical tracks in Figure 3 might produce such a gap. As expected, the flash-mixed models are separated by a gap of

~ 0.5 mag in V from the hot end of the canonical EHB. Our simulations, which include evolution off the ZAHB, predict an EHB gap close to that observed in NGC 2808 (see Brown et al. 2001). A similar EHB gap is not seen in ω Cen, possibly because it has been obscured by the metallicity spread of the cluster.

5. Conclusions

- Stars which ignite helium on the white-dwarf cooling curve will undergo substantial mixing between the helium core and hydrogen envelope during the helium flash. This flash-induced mixing will greatly enhance the envelope helium and carbon abundances.
- Flash-mixed EHB stars will appear subluminous in UV color-magnitude diagrams due to their redistributed far-UV flux and larger bolometric corrections, in agreement with the subluminous stars in ω Cen and NGC 2808.
- Flash mixing leads to a dichotomy in the properties of EHB stars. The temperature gap between the flash-mixed and canonical (i.e., unmixed) stars may explain the EHB gap found in optical CMDs of NGC 2808.
- Flash mixing on the white-dwarf cooling curve may provide a new evolutionary channel for producing H-deficient stars, particularly the high gravity, He-rich sdO stars (Lemke et al. 1997) and the minority of sdB stars that are He-rich (Moehler, Heber, & Durrell 1997).

References

- Bedin, L. R., Piotto, G., Zoccali, M., Stetson, P. B., Saviane, I., Cassisi, S., & Bono, G. 2000, *A&A*, 363, 159
- Brown, T. M., Sweigart, A. V., Lanz, T., Landsman, W. B., & Hubeny, I. 2001, *ApJ*, in press (astro-ph/0108040)
- Castellani, M., & Castellani, V. 1993, *ApJ*, 407, 649
- D'Cruz, N. L., Dorman, B., Rood, R., & O'Connell, R. 1996, *ApJ*, 466, 359
- D'Cruz, N. L., O'Connell, R. W., Rood, R. T., Whitney, J. H., Dorman, B., Landsman, W. B., Hill, R. S., Stecher, T. P., & Bohlin, R. C. 2000, *ApJ*, 530, 352
- Iben, I., Jr. 1976, *ApJ*, 208, 165
- Iben, I., Jr. 1995, *Phys. Rep.*, 250, 1
- Lemke, M., Heber, U., Napiwotzki, R., Dreizler, S., & Engels, D. 1997, in *The Third Conference on Faint Blue Stars*, ed. A. G. D. Philip, J. W. Liebert & R. A. Saffer (Schenectady: L. Davis Press), 375
- Moehler, S., Heber, U., & Durrell, P. R. 1997, *A&A*, 317, L83
- Sosin, C., Dorman, B., Djorgovski, S. G., Piotto, G., Rich, R. M., King, I. R., Liebert, J., Phinney, E. S., & Renzini, A. 1997, *ApJ*, 480, L35
- Sweigart, A. V. 1997, in *The Third Conference on Faint Blue Stars*, ed. A. G. D. Philip, J. W. Liebert & R. A. Saffer (Schenectady: L. Davis Press), 3
- Walker, A. R. 1999, *AJ*, 118, 432